Theoretical evaluation of wind-generator potentiality in Jordan using the site effectiveness approach

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Wind data over many years had been used for a feasibility analysis of optimum future utilization of wind-generator potentiality in twenty-two sites, covering all landscape types and regions in Jordan. The yearly mean wind speed and the yearly average available wind energy flux were computed for each site. Yearly mean wind speeds at a height of 24m could reach as high as 7.6 m/s and available wind energy flux close to 3 MWh/m^2/yr could be attained. Detailed technical assessment, for nine most promising potential wind sites, was made using the site effectiveness approach. The maximum site effectiveness and its corresponding cut-in speed were indicated. The investigation was performed assuming three models of small and medium size wind machines representing different ranges of characteristic speeds and rated power. The results had shown that small and medium wind turbines could be installed at the highlands and desert regions which can be utilized for water supply and electrical power generation, provided the correct selection of wind machine-site is made.

تم استخدام بيانات سرعة الريح عبر عدة سنين لدراسة جدوى الاستخدام المستقبلي لطاقة الرياح في اثنين وعشرين موقعا بالأردن تغطي كافة مناطق المملكة. كما تم حساب المعدل السنوي لسرعة الرياح والمعدل السنوي لتدفق طاقة الرياح لكل من هذه المواقع. وصل المعدل السنوي لسرعة الرياح في بعض المناطق إلى ٧،٦ م/ث على ارتفاع ٢٤ م في حين وصل تدفق طاقة الرياح إلى ٣ ميجاوات.ساعة/م^2/سنة. وبناء على ذلك فقد تم التقييم الفني المفصل لأفضل تسعة مواقع باستخدام طريقة كفاءة الموقع والتي استخدمت لاول مرة في الأردن. و في هذا السياق فقد تم حساب أعلى كفاءة موقع و أدنى سرعة تشغيل مرادفة لهذا الموقع باستخدام ثلاثة نماذج لتوربينات الهواء ذات الأحجام الصغيرة والمتوسطة بحيث تمثل مختلف الفئات من حيث الخواص الهندسية و معدلات الطاقة الناتجة. وتدل النتائج على إمكانية استخدام مولدات صغيرة و متوسطة الحجم في الصحراء و في المناطق المرتفعة لضخ المياه و توليد الكهرباء شريطة الاختيار الأمثل للموقع و للآلة المناسبة له.

Keywords: Wind energy, Wind turbines, Wind-generator potentiality, Site effectiveness

1. Introduction

Many scientists, at present, seem to regard renewable energy as the only viable alternative to the present sources of energy where unwanted emissions have to be minimized. The development of new renewable energy technology has advanced steadily over the past few decades, and the basic research has been completed with the requirement now is to improve reliability, reduce costs and establish commercial viability. However, the capture area of renewable energy is large, and the equipment is capital intensive.

The environment sources of renewable energy may be natural or human. One of the natural environment sources is wind energy. A Wind Energy Conversion System (WECS), however, is required to extract the energy from the wind. Such system would operate at maximum efficiency, only if it is designed for the site where it is to be set up. The rated power, cut-in, rated and cut-off wind speeds would be defined according to the site. These parameters can be chosen so as to maximise the delivered energy for a given amount of available wind energy. However, it is rather expensive to design WECS for one site, and usually one chooses for a given site the best among existing machines. It is possible, nonetheless, to investigate the potentiality of a site in relation to a wind machine by means of the site effectiveness model of the energy exchange between WECS and wind distribution.

Wind power has been utilized commercially. In the United States, for example, wind

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farms have been set-up that contain thousands of wind wheels. With good planning of the energy supply for the future, wind power can cover a substantial sector of the global electricity demand, perhaps as much as 20% or more.

The energy situation in Jordan as the situation in other parts of the world has led to the consideration of renewable energy utilization. Using new sources of energy would assist in meeting the increase in the energy demand in Jordan for the foreseeable future exerted by the rapid expansion of industrial projects and the increase in the socio-economic growth. The future expectations of Jordan's primary energy sources in the year 2010 are planned to include 5% renewable energy.

Reasonable wind energy potential is expected in many parts of Jordan. The scope of wind electricity generation seems to be limited to some areas with a small demand but is economically and technically feasible. Grid connected electricity generation is the most promising wind energy application as the area with the highest average wind speed is also the area in which the main lines of the national electricity grid are concentrated. The scope of mechanical wind pumps, however, is limited to regions with shallow wells or in places with a small demand. In most parts of Jordan the ground water table is too low, which makes wind electric pumping systems an interesting option for pumping water in large quantities and/or over higher heads providing the wind speed is high enough for economic feasibility. All water pumping for pumping head smaller than 10 m as in the Jordan valley is now done by electric and diesel pumps. Possible replacement of existing pumps by wind pumps is slim, as the wind speeds in the valley are low, and the infrastructure is such that the supply of electricity and diesel fuel is assured at relatively low cost in the valley. Nevertheless, there might be possibilities for water supply using wind power in the desert area, where pumping heads are high ranging from 100 to 200 m, since the cost of power supply by fuel would be very high due to transportation costs.

The application of wind energy in Jordan, so far, has been for the connection of wind turbines to main grid-system or to small local grids for rural communities, battery charging and private residence water heating in addition to water pumping in remote areas in the arid land. The experimental station for generating electricity by wind energy, which is composed of four wind generators, located at Ibrahimia in northern Jordan since 1988 produce 80 kW each. The average capacity factor of the station is 24% and the availability of the turbines is about 96%. There are also two wind energy converters, each produces 20 kW of energy, are installed in 1987 at Jurf El-Darawish village in the southern semi-arid region.

Many workers had examined wind energy potential in one selected location or more in Jordan, e.g. [1-5]. Their work was based mainly on the Weibull model, which is not enough reliable for the prevision of the energy output of a WECS as it does not consider the real interaction between wind machine and site [6]. The goal of this study is, therefore, to evaluate the wind energy distribution in Jordan, based on the climatological data over many years, and to make a feasibility analysis for optimum future utilization of wind-generator potentiality in Jordan employing the site effectiveness approach, in an endeavour to assess the usage of small and medium size wind machines to pump water and generate electricity.

2. Topography of Jordan

Jordan is confined between 29° to 33.5° latitude and 35° to 39° longitudes, and have a total area of 91,878 km^2 of around 4.7 million total populations with an annual population growth of 4 - 4.5%. Jordan can be divided geographically into the following three major regions (see fig. 1):

- *Region (A)*, the Jordan rift valley (Ghor) region, the whole of which is below sea level and occupies around 6% of Jordan's total area which is occupied by less than 5% of the total population. It has a width varying from 5 to 25 km and stretches from north to south with the Dead Sea in the middle. It slopes down from 210 m in the north to 407 m below sea level at the Dead Sea. Further south the level goes up through Wadi Araba to about sea level at

Aqaba.

- *Region (B),* the highland and plain plateau region is a hilly area extending east of the rift valley from north to south with the plain plateau east of the highland extending also from north to south. This region occupies about 14% of Jordan's whole area and nearly 85% of the population lives in this region. Part of the hilly area contains rugged terrain and crossed by numerous deep valleys. The elevation of the highland area varies between 600 to 1500 m above sea level.
- *Region (C),* the semi-arid region, which occupies roughly 80% of the total area of Jordan, extends to the east of the plain plateau area from north to south. The remaining population of 10% lives in this area, mainly in the northern part and close to the desert highway in the south, with the southern desert is basically uninhabited.

Fig. 1. Location of sites and regions of Jordan.

It can be seen that Jordan's topography is very diverse which leads to some differences in wind speed over Jordan. Thus the chosen wind stations are distributed to cover all of the diverse regions in Jordan.

3. Energy conversion model

The energy conversion model of [6] is used in the analysis of the available wind data in Jordan for wind-turbine siting and potentiality. The commonly used Weibull and Rayleigh models to describe the available wind distribution and consequently analyse the wind energy exchange of WECS are not enough reliable for the prevision of the energy output of a WECS [6]. The available power P_a of a wind turbine is related to the output power of a WECS, P, by the following relation,

$$P = \eta P_a = \eta\left(\frac{1}{2} m V^2\right) = \frac{1}{2}\rho\eta A V^3, \tag{1}$$

where $m = \rho A V$ is the air mass flow rate, η is the WECS overall efficiency that takes into account the mechanical, electrical, aerodynamic efficiencies and the correction for the effective available power, ρ is the air density and V is the wind speed.

The available wind energy, E_a, for a constant wind speed, in the period T is,

$$\begin{aligned} E_a &= \int_T P_a dt = \frac{1}{2}\rho A \int_T V^3 dt = \frac{1}{2}\rho A T V_{m3}^3 \\ &= E_{as} A, \end{aligned} \tag{2}$$

where V_{m3} and E_{as} are the cubic mean wind speed and the available energy flux in the period T.

The analytical law of the power curve of a turbine between the cut-in speed, V_c, and the rated speed, V_r, (see fig. 2) is simulated according to the model used. Models either use linear, quadratic or power-law.

A power law for the speed range $V_c \leq V \leq V_r$ may be written as [6].

$$P = P_r \frac{V^2 - V_c^2}{V_r^2 - V_c^2}, \tag{3}$$

and,

$P = P_r$ for $V_r \leq V \leq V_f$,
$P = 0$ for $V \leq V_c$ and $V \geq V_f$.

Suitable to simulate the power curve of a pitch-controlled wind turbine and to a lesser extent a stall- or a yaw- controlled wind turbine, which do not have a constant power range and thus neglects the power output exceeding P_r. The overall efficiency η in this model takes the form,

$$\eta = \eta_r \frac{V_r^3}{V^3} \frac{V^2 - V_c^2}{V_r^2 - V_c^2} \qquad \text{for } V_c \le V \le V_r \,, \tag{4}$$

and,

$$\eta = \eta_r \frac{V_r^3}{V^3} \qquad \text{for } V_r \le V \le V_f \,, \tag{5}$$

where,

$$\eta_r = \frac{P_r}{\frac{1}{2}\rho A V_r^3} \,, \text{ is the rated value of } \eta. \tag{6}$$

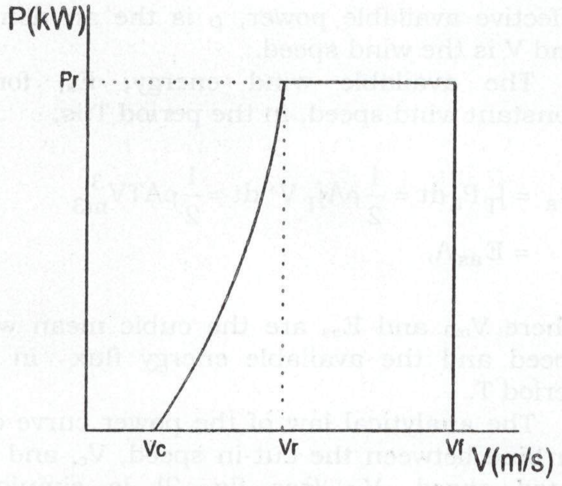

Fig. 2. Typical WECS power curve.

The maximum of η (design efficiency) falls into the power law range, V_c-V_r, and is calculated by [6],

$$\eta_{max} = \frac{\eta_r V_r^3}{2.6 V_c \left(V_r^2 - V_c^2\right)} \,,$$

and,

$$V_{op} = 1.73 V_c \,, \tag{7}$$

where V_{op} is the wind speed at which maximum efficiency is achieved.

By denoting f_1 and f_2 as the overall wind-speed frequencies in the power-law range (V_c-V_r) and the constant power range (V_r-V_f), respectively, and V_{m2} the quadratic mean wind speed in the power law range, the output energy, E, of the system in the period T is calculated as follows,

$$E = \int_0^T P dt = 2.6 K A \eta_{max} V_c T \left[f_1\left(V_{m2}^2 - V_c^2\right) + f_2\left(V_r^2 - V_c^2\right)\right] \tag{8}$$

Introducing the site coefficient, ε, as the ratio between the output energy E and the maximum available energy converted by WECS running at constant design efficiency $\eta_{max} E_a$, i.e.,

$$\varepsilon = \frac{E}{\eta_{max} E_a} = \frac{2.6 V_c}{V_{m3}^3}\left[f_1\left(V_{m2}^2 - V_c^2\right) + f_2\left(V_r^2 - V_c^2\right)\right] \tag{9}$$

The output energy E and its flux per unit area E_s can thus be written as,

$$E = \varepsilon \eta_{max} E_a,$$

$$E_s = E/A = \varepsilon \eta_{max} E_{as} \,. \tag{10}$$

The site efficiency ε measures the fraction of the maximum available energy that can be delivered by a WECS. It depends only on the local wind frequency distribution and on the characteristic speeds of the turbine, and ranges from 0 – 0.99, while the design efficiency η_{max} depends on the whole system and is not variable for a system, and ranges from 0.25 – 0.35. Therefore, ε affects the energy output much more than η_{max}, and can be analyzed for definite periods, e.g. months or seasons. Thus, ε is more suitable to evaluate the site potentiality.

4. Sites chosen

The sites whose main wind data have been used in this work are presented in table 1. All quantities in the table were evaluated as yearly mean value over an entire period of ten years (1989-1998), although the quantities for the sites with asterisk (*) were calculated over a period of three years (1992-1994) as there were only 3 years of data available. In table 1 the sites are aggregated in the three geographic regions, (A) ghor region, (B) highland region and (C) semi-arid region. The main wind data was measured at an elevation, hr, of 10 m, but the chosen wind generators hub height, h, is at 24 m. Therefore, the wind data have been normalised at 24 m of elevation using the following formula [7],

$$\frac{V_h}{V_{hr}} = \frac{\ln\left(h/z\right)}{\ln\left(hr/z\right)},$$

where, V_h is the wind speed at height h, V_{hr} is the wind speed at the reference height hr, and z is the roughness height; taken as 0.20 for the sites of region (A), 0.25 for those of region (B), and 0.05 for those of region (C) based on the topography of these regions.

5. Models of WECS

Three models of wind energy generators are considered (see table 2):

(A) Small size, nominated rpm 775 revs/min, permanent magnet generator with nominated voltage of 12 or 24 volts DC; blade design = GFK fixed; model = LMW 1003.

(B) Small size, nominated rpm 60-350 revs/min, permanent magnet generator with nominated voltage of 240 volts, 60 Hz, AC, or 120 volts DC; blade design = GFK fixed; model = LMW 10/7.

(C) Medium size, nominated rpm 48 revs/min, generator rpm of 1500 revs/min and of nominated voltage of 380 volts; blade design GFK fixed; model = FGW (Renk Tacke) TW 150.

The models chosen represent different ranges of characteristic speeds and rated power. In addition, they have different fields of application. Both of models (I) and (II) are small size wind turbines, suitable for low energy needs (water pumping and/or electric supply) in remote areas, although their design, performance and environmental needs are quite different, whereas model (III) is suitable for small electric networks or for grid connection.

Table 1
Main wind data of the sites

Region	Site	Symbol	V_m (m/s)	V_{m3} (m/s)	E_{as} (kWh/m²/yr)
(A)	Baqura	A01	1.38	1.48	17.5
	Deir Alla	A02	2.77	3.02	148.4
	Aqaba	A03	5.79	6.43	1432.2
(B)	Irbid	B01	3.75	4.35	443.5
	Ras Muneef	B02	7.42	8.09	2852.5
	Swaileh	B03	4.28	4.58	517.6
	Amman	B04	3.71	4.19	396.3
	Salt*	B05	4.53	4.98	665.4
	Madaba*	B06	3.12	3.37	206.2
	Er-Rabba*	B07	2.61	2.92	134.1
	Tafileh*	B08	6.40	7.23	2036.1
	Shoubak*	B09	2.78	3.11	162.1
(C)	Rwaished	C01	3.68	4.12	376.8
	Mafraq	C02	2.89	3.29	191.9
	Q.A.I. Airport	C03	4.43	4.83	607.0
	Al-Jafer	C04	3.19	3.54	239.0
	Safawi*	C05	4.49	4.94	649.5
	Wadi Dhulail*	C06	2.44	2.66	101.4
	Azraq South*	C07	4.49	7.97	661.4
	Daba'a*	C08	7.59	8.20	2970.4
	Qatraneh*	C09	3.29	3.52	235.0
	Ma'an*	C10	3.15	3.40	211.7

Table 2
Main data of the three WECS models

Model	P_r (kW)	No. of blades	Rotor dia. (m)	Swept area (m^2)	V_c (m/s)	V_r (m/s)	V_f (m/s)	V_{op} (m/s)	η_r	η_{max}
(I)	1.0	3	3.0	7.1	2.5	9.0	20.0	4.3	0.314	0.471
(II)	10.0	3	7.0	38.5	3.0	12.0	30.0	5.2	0.244	0.400
(III)	150.0	3	20.5	330.1	4.0	14.0	24.0	6.9	0.269	0.394

5. Discussion of results

All of the results are integral quantities calculated over an entire number of years, and the energy terms are yearly averages. Table 1 collects the main wind data for representative and promising sites of the three regions of Jordan. In this table, the yearly mean velocity at a height of 24 m, and the available wind energy flux (kWh/m^2/yr) computed directly by the wind data are presented. It can be seen that the yearly mean wind speeds in some locations could reach as high as 5.8, 7.4 and 7.6 m/s in regions (A), (B) and (C), respectively. However, the sites with high energy level, demarcated by a threshold of 1MWh/m^2/yr of available energy flux E_{as}, are limited to four locations; A03, B02, B08, and C08, two of which are in the mountainous region.

Table 3 gives the results of the matching of the WECS models with the wind distribution for the expected high-potential wind generation sites in the three regions. In table 3, the three lines of values at each chosen site respectively are ε, E_s (in kWh/m^2/yr) and E (in MWh/yr) for the three models on the site. The site effectiveness, ε, achieves a maximum and depends only on kinematic parameters, concentrated mainly on the effect of V_c and V_r, and hence ε is the most significant parameter. It is apparent that the energy output, E, is larger for the model with the larger model swept area for any site, although the value of the output energy flux, E_s, is dependent on the various parameters governing the wind machine, site effectiveness and site wind data.

Table 3
Values of ε, Es, and E for some sites of high wind-generator potentiality

Site	Model (I)			Model (II)			Model (III)		
	ε	E_s	E	ε	E_s	E	ε	E_s	E
A03	0.757	510.6	3.63	0.828	474.2	18.26	0.843	475.7	157.00
B02	0.658	884.0	6.28	0.752	858.0	33.034	0.865	972.2	320.90
B03	0.905	220.6	1.57	0.885	183.2	7.05	0.638	130.1	42.95
B05	0.863	270.5	1.92	0.868	231.0	8.89	0.639	167.5	55.30
B08	0.692	663.6	4.71	0.774	630.4	24.27	0.840	673.9	222.40
C03	0.876	250.4	1.78	0.860	208.8	8.04	0.650	155.4	51.32
C05	0.502	153.6	1.09	0.473	122.9	4.73	0.324	82.9	27.37
C07	0.913	284.4	2.02	0.972	253.3	9.752	0.880	229.3	75.70
C08	0.745	1042.3	7.40	0.753	894.7	34.45	0.872	1020.5	336.88

Fig. 3 shows a plot of ε against V_c at constant V_r for the site of Ras Muneef (B02), with the operative points of the models I, II and III marked on. For any rated speed ε gets a maximum that depends on the site and on V_r. At a given V_r there is one value of V_c ($V_{c,op}$) that maximises the fraction of available energy the machine is able to yield, so that a wind turbine of given rated speed should have the respective optimum cut-in speed to be able to extract really the maximum energy from the wind. It can be seen from fig. 3 that the ε curves for the site B02 at $V_r \geq 10$ m/s fall on the same curve, and $V_{c,op}$ = 4.5 m/s for the three wind machines chosen in this study.

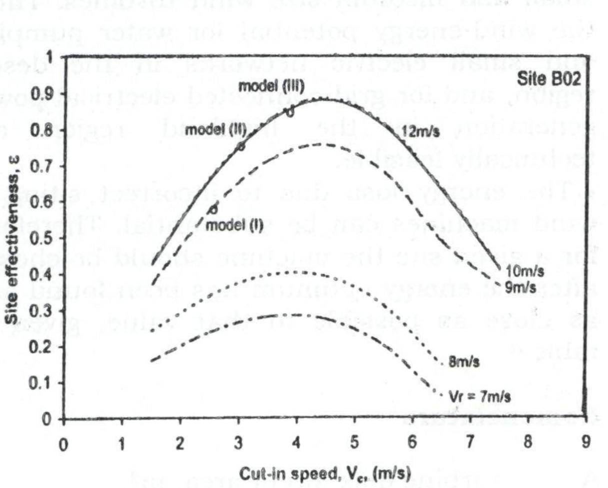

Fig. 3. Site effectiveness versus cut-in speed at constant rated speed.

The site effectiveness of the representative promising sites of table 3 against cut-in speed aggregated by model of WECS is presented in fig. 4. The operative points of each model are indicated in the figure. It is obvious that choosing the wrong model for a site can be very penalising. As can be seen, at site B02 model (I) achieves ε = 0.575 and model (III) ε = 0.867. Conversely, on site B03 model (III) achieves 0.466 and model (I) 0.825. Thus, it is well known that no one should install model (I) in site B02, or model (III) in site B03, and so on. Therefore, careful choice of the WECS avoids decrease of effectiveness. In poor sites, where the available wind energy is very little, such sites can deliver something only if the wind machine matches the local maximum effectiveness, i.e. V_c is low, which takes place when V_r is low as well. Although V_r and V_c of a WECS are interdependent, ε is mainly optimised by V_c. The correct choice of a wind machine for a site is, therefore, based on the site effectiveness ε for that site. The local maximum site effectiveness and the corresponding cut-in speed for the high wind-generator potentiality sites in the three regions are outlined in table 4.

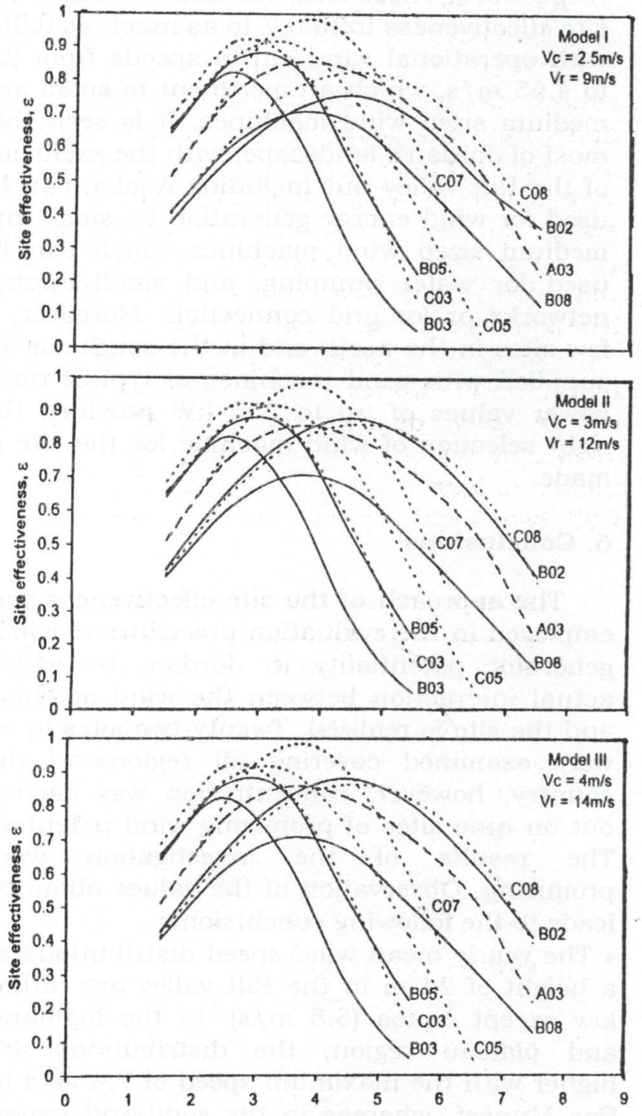

Fig. 4. Site effectiveness of promising sites versus cut-in speed for the three models of WECS.

Table 4

Maximum site effectiveness and corresponding cut-in speed for high wind-generator potentiality sites

Site	A03	B02	B03	B05	B08	C03	C05	C07	C08
ε_{max}	0.855	0.877	0.825	0.882	0.708	0.923	0.916	0.985	0.861
$V_{c,op}$ (m/s)	3.70	4.44	2.50	2.95	3.70	2.72	3.14	3.73	4.65

In table 4 the high prospective wind-generator sites in Jordan are analysed with respect to ε. These sites can achieve maximum site effectiveness from 0.7 to as much as 0.985 with operational wind cut-in speeds from 2.5 to 4.65 m/s, which are pertinent to small and medium sized wind machines. It is seen that most of Jordan's landscape, with the exclusion of the Rift valley but including Aqaba, can be used for wind energy generation by small and medium sized wind machines which can be used for water pumping, and small electric networks or for grid connection. Moreover, a few sites in the north and in the south can be supplied with wind machines of typical rated power values of up to 250 kW provided the right selection of wind machine for the site is made.

6. Conclusions

The approach of the site effectiveness was employed in the evaluation procedure of wind-generator potentiality in Jordan, by which actual interaction between the wind machine and the site is realized. Twenty-two sites in all were examined covering all regions of the country, however, concentration was carried out on nine sites of promising wind potential. The results of the investigation were promising. Observation of the values obtained leads to the following conclusions:

- The yearly mean wind speed distributions at a height of 24 m in the Rift valley are rather low except Aqaba (5.8 m/s). In the highland and plateau region, the distributions are higher with the maximum speed of 7.4 m/s in Ras Muneef, whereas in the semi-arid region they are somewhat slightly lower than in the highland, however, Daba'a reached a mean speed of 7.6 m/s. These sites could achieve yearly mean available energy flux of 1432, 2852, 2970 kWh/m²/yr, respectively.
- The high-energy level sites in Jordan can attain maximum site effectiveness between 0.7 and 0.985 with operational cut-in speeds form 2.5 to 4.65 m/s that are characteristic of small and medium size wind turbines. Thus, the wind-energy potential for water pumping and small electric networks in the desert region, and for grid-connected electrical power generation in the highland region are technically feasible.
- The energy loss due to incorrect siting of wind machines can be substantial. Therefore, for a given site the machine should be chosen after the energy optimum has been found and as close as possible to that value, given in table 4.

Nomenclature

A	turbine disk swept area, m²,
E	output energy, MWh/yr,
E_a	available wind energy, MWh/yr,
E_{as}	available wind energy flux per unit swept area, MWh/yr/m²,
E_s	output energy flux, MWh/yr/m²,
f(V)	wind speed frequency distribution function,
f_1	$= \int_{V_c}^{V_r} f(V)dV$, wind presence frequency in the range V_c-V_r,
f_2	$= \int_{V_r}^{V_f} f(V)dV$, wind presence frequency in the range V_r-V_f,
m	air mass flow rate, kg/s,
P	power output, kW,
P_a	available wind power, kW,
P_r	rated output power of the turbine, kW,
t	time, hr,
T	entire time period, hr,
V	wind speed, m/s,

V_c	cut-in wind speed, m/s,
$V_{c,op}$	cut-in wind speed at maximum site, effectiveness at given V_r, m/s,
V_f	cut-off wind speed, m/s,
V_m	mean wind speed, m/s,
V_{m2}	$= \int_{V_c}^{V_r} f(V)V^2 dV$, quadratic mean wind speed in the range V_c-V_r, m/s,
V_{m3}	$= \frac{1}{T}\int_0^T V^3 dV$, cubic mean wind speed in the period T, m/s,
V_{op}	wind speed of maximum turbine efficiency, m/s,
V_r	rated wind speed, m/s,
E	site effectiveness,
η	WECS overall efficiency,
η_r	rated value of η,
η_{max}	maximum value of η, and
ρ	density of air, kg/m^3.

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